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Invited Paper

Adaptive interferometric velocity measurements using a laser guide star

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ABSTRACT

We have harnessed the power of programmable photonics devices for an interferometric measurement technique. Laser interferometers are widely used for flow velocity measurements, since they offer high temporal and spatial resolutions. However, often optical wavefront distortions deteriorate the measurement properties. In principle, adaptive optics enables the correction of these disturbances. One challenge is to generate a suitable reference signal for the closed loop operation of the adaptive optics. An adaptive Mach Zehnder interferometer is presented to measure through a dynamic liquid-gas phase boundary, which can lead to a misalignment of the interfering laser beams. In order to generate the reference signal for the closed loop control, the Fresnel reflex of the phase boundary is used as Laser Guide Star (LGS) for the first time to the best of the authors' knowledge. The concept is related to the generation of artificial stars in astronomy, where the light transmitted by the atmosphere is evaluated. However, the adaptive interferometric flow velocity measurements at real world experiments require a different concept, since only the reflected light can be evaluated. The used LGS allows to measure the wavefront distortions induced by the dynamic phase boundary. Two biaxial electromagnetically driven steering mirrors are employed to correct the wavefront distortions. This opens up the possibility for accurate flow measurements through a dynamic phase boundary using only one optical access. Our work represents a paradigm shift in interferometric velocity measurement techniques from using static to dynamic optical elements.

Keywords: adaptive optics; Gaussian laser beam, Fresnel laser guide star; deflectometry, control loop, Mach-Zehnder interferometer

1. INTRODUCTION

Laser interferometers have become a well-established and indispensable tool for precision measurements in a huge variety of scientific and industrial applications, especially in fluid mechanics. Common measurands are displacement and velocity, which are proportional to the interference signal phase and frequency, respectively. It is well known that temperature, pressure and concentration variations of the ambient air change the refractive index [1]. Typical examples in the area of fluid mechanics are temperature gradients in combustions and pressure gradients at shock waves in compressible fluids. Beside such refractive index gradients also fluctuating interfaces between two media of different optical density have to be considered. Typical examples in fluid mechanics are water channel flows with an open surface, multi-phase flows, blood flows, levitated oscillating droplets and flows alongside a phase boundary. These variations cause severe distortions of the optical wavefronts, which can result in a failure or not tolerable uncertainties of the measurements. To overcome these challenging metrological problems, the employment of adaptive optics (AO) for a smart laser interferometer is proposed. AO is predominantly known from astronomy, where it has boosted the capabilities of modern earth-bound telescopes [2–5]. In general, an AO system comprises a wavefront sensor to measure the distortion of the wavefronts, an electric control circuit and an optical modulator to correct the distortions. Wavefront

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distortions caused by turbulent fluctuations of the earth's atmosphere are compensated resulting in a nearly diffraction-limited performance. A further prominent area of AO is ophthalmology. The correction of the eye aberrations enables to resolve single cells in the retina e.g., by using confocal microscopy [6] or optical coherence tomography (OCT) [7].

Also in technical metrology AO has been employed already. At optical roughness measurements of technical surfaces, the aberrations along the propagation direction of the laser beam have been corrected [8,9]. Also for flow measurements AO has been used [10–12]. First approaches have been demonstrated at laser Doppler velocimetry (LDV). AO was inserted to compensate for the random measurement deviation due to temperature gradients of heated air [10]. The LDV has been used to study gas flow stratifications. Recently, modern AO systems have been employed for an interferometric LDV [11,12]. The deployed AO devices were supplied by Flexible Optical B.V. (OKO tech, The Netherlands) and consist of a deformable membrane mirror with integrated tip-tilt stage, a Hartmann-Shack wavefront sensor and a controller based on a PC. This adaptive LDV provide flow velocity measurements through fluctuating gas-liquid interfaces inside a water basin or channel with an open surface [11]. The distortions of the propagating laser beams due to the water surface waves have been corrected successfully, but to wave heights of only a few 10 microns [12]. At some tasks in fluid mechanics higher wave heights appear, resulting in larger amplitudes of optical distortions. In this paper we present a different approach for an adaptive, smart, interferometric LDV to overcome the former limitations. A commercially available galvanometer steering mirror are used to provide a large stroke for the wavefront correction.

For the first time, we investigate the hypothesis that electrically tunable lenses and steering mirrors enable the correction of large optical distortions in interferometry. The presented smart LDV interferometer will enable accurate flow velocity measurements through disturbing media interfaces especially at fluctuating gas-liquid interfaces. It faces large optical wavefront distortions caused by high surface waves of liquid flows, e.g., at film cooling processes, seawater salt removal, fractional distillation or processes to cool reactors.

2. VELOCITY MEASUREMENTS THROUGH A FLUCTUATING GAS-LIQUID INTERFACE

2.1 Preconsiderations

The flow velocity is gathered by an interferometric LDV technique, which allows high spatial and temporal resolutions together with a low velocity measurement uncertainty. The basic principle is to intersect two coherent laser beams under a small angle, forming a Mach-Zehnder interferometer. In the volume of intersection, a system of almost parallel interference fringes develops. If a particle carried with the flow to be investigated passes through the intersection volume of the laser beams, it scatters light that is modulated in amplitude with the Doppler frequency f. The velocity component v_x perpendicular to the interference fringe system orientation is resulting to

$$v_x = f \cdot d \quad , \tag{1}$$

with the measured Doppler frequency f [13]. The a-priori calibrated interference fringe spacing d is calculated by

$$d = \frac{\lambda}{2\sin\theta}\left(1+\frac{z\cos^2\theta(z\cos^2\theta\text{-}z_W)}{z_R{}^2\cos^2\theta\text{-}z_W(z\cos^2\theta\text{-}z_W)}\right) \quad , \tag{2}$$

with λ as the laser wavelength, θ as the intersection half angle of the interfering laser beams, z as the axis along the bisecting line of the two laser beams, z_W as the axial shift of the beam waist position relative to the center of the measurement volume and z_R as the Rayleigh length of the Gaussian laser beams, which is defined by $z_R = \pi w_0^2/\lambda$, where w_0 is the radius of laser beam waists [13].

Considering the propagation of the laser beams through an open water surface to measure the flow velocity inside the water basin, the measurement properties of an LDV are changed by a moving air-water interface. In order to evaluate the contributions of different effects, the height function *h(x,t)* of the air-water interface is developed into a Taylor series. This procedure is in analogy to the representation with Zernike polynomials. For simplification, only the one-dimensional expression is considered:

$$h(x,t) = \underbrace{h(x_0,t)}_{Stroke} + \underbrace{(x-x_0)\left.\frac{\partial h(x,t)}{\partial x}\right|_{x=x_0}}_{Tilt} + \underbrace{\tfrac{1}{2}(x-x_0)^2\left.\frac{\partial^2 h(x,t)}{\partial x^2}\right|_{x=x_0}}_{Curvature} + \ldots \tag{3}$$

The optical distortions caused by the fluctuating air-liquid interface can deteriorate the measurement properties as follows:

- 0th order: Height or stroke of the air-water interface. For a lift of the interface a parallel shift of the beam occurs whereas the beam direction remains constant. The consequence is a shift of the position of the measurement volume, i.e., a dislocation of the measurement position. Furthermore a signal frequency jitter is introduced, when the air-water interface is moving up or down.
- 1st order: Tilt of the air-water interface. Due to refraction, a tilt of the interface will change the propagation direction of the laser beam. Going to the two-dimensional consideration, it has to be distinguished between a tilt in the plane spanned by the two partial beams δx and a tilt in the direction normal to this plane δy.

  (a) Tilt δx in x-direction (tip):

  On one side a displacement of the measurement position results and on the other side there is a change in the intersection half angle θ of the interfering laser beams. Due to a change of the Rayleigh length z_R or the beam waist position z_w a variation of interference fringe spacing d results, see Equation (2). The standard deviation σ_d represents these variations. Using Equation (1) and the propagation law of statistical independent measurement, uncertainties of the fringe spacing σ_d and the signal frequency σ_f the relative velocity measurement uncertainty yields to [13]

$$\frac{\sigma_{v_x}}{v_x} = \sqrt{\left(\frac{\sigma_f}{f}\right)^2 + \left(\frac{\sigma_d}{d}\right)^2} \tag{4}$$

  (b) Tilt δy in y-direction:

  A beam deflection in the y-direction normal to the plane spanned by the two Gaussian beams will result in skew rays. The reduced overlap of the partial laser beams results in lower interference visibility and signal-to-noise ratio (SNR). Only measurement signals with a sufficient SNR are considered for further evaluation. The corresponding validation rate is given by the ratio between the evaluable and all signals detected. It represents a crucial figure-of-merit of the LDV system, since on the one hand the maximum frequency bandwidth of the velocity fluctuations and on the other the effective measurement time is determined. In the worst case of negligible laser beam overlapping no measurements can be performed at all, represented by a validation rate of zero.
- 2nd order: Parabolic curvature of the interface. Due to refraction, a curvature of the interface induces a lens effect on the beam propagation. It changes the radius of the beam waist w_0 and the position z_W of the beam waist. As a consequence, the fringe spacing d is changed according to Equation (2), which in general enhances the velocity measurement uncertainty, see Equation (4).
- 3nd order and higher orders: Distortions of the surface with high spatial frequency. The wavefront of the laser beams will be locally distorted, leading to inhomogeneities in the interference fringes. The fringe spacing can vary in all three directions. In consequence, the measurement uncertainty will increase, see Equation (4).

It should be noted that the different distortion orders strongly depend on the incidence point of the beam with respect to the surface wave, i.e., on the phase of the wave. If the beam passes through a maximum of the water wave, a convergent lens will mainly affect the beam, if it passes through a minimum, a divergent lens effect appears. If the beam propagates through the zero-crossing of the wave, mainly a beam deflection and a phase jitter will occur.

A previous experimental analysis revealed that low-order Taylor series orders, respectively Zernike polynomials (piston/stroke, tip/tilt and defocus) dominate the wavefront distortions [12]. Distortions of higher orders, i.e., with higher spatial frequency can be neglected at the considered flow measurement task. This can be easily understood since at the water surface the diameter of the laser beams is around some millimeters and therefore significantly smaller than the typical wavelength of the observed capillary waves of 50 mm. This wavelength results by considering the highest amplitude (mode) of the measured Fourier spectrum of 6 Hz and the estimated phase velocity of the surface wave of 0.3 m/s.

These preconditions define the spatial and temporal parameters of the AO system to be implemented. In general, several optical modulators are available for the correction of wavefront distortions, e.g., deformable membrane mirrors, micro-electro-mechanic-system (MEMS) mirror arrays and liquid-crystal spatial light modulators [14-17]. In our former research work [11,12] we have employed a deformable membrane mirror exhibiting 17 electrostatic actuator elements and built-in piezoelectric tip-tilt unit. An obstacle of the deformable membrane mirror was its restricted correction amplitude of the wavefronts. In the next section we will present a new optical measurement system able to handle the correction of large distortion amplitudes and to use only a single optical access by taking into account a Fresnel guide star.

2.2 Investigations on flow velocity measurements

Laser-based flow velocity measurements play an important role in versatile application fields [18-20]. In this contribution we study the velocity measurements inside a water basin by a laser Doppler velocimeter, based on a Mach-Zehnder interferometer setup. The distortions of the dynamic air-water interface can be corrected using an adaptive optics system. A Hartmann-Shack (HS) sensor was used at a first experimental setup to measure the wavefront distortions and a standard PC to calculate the actuating variables. The HS sensor was placed underneath the basin with the consequence that the parameters of the measured transmitted beam are stabilized. However, real world experiments allow only single optical access measurements, i.e. the reflected light instead of the transmitted light has to be evaluated.

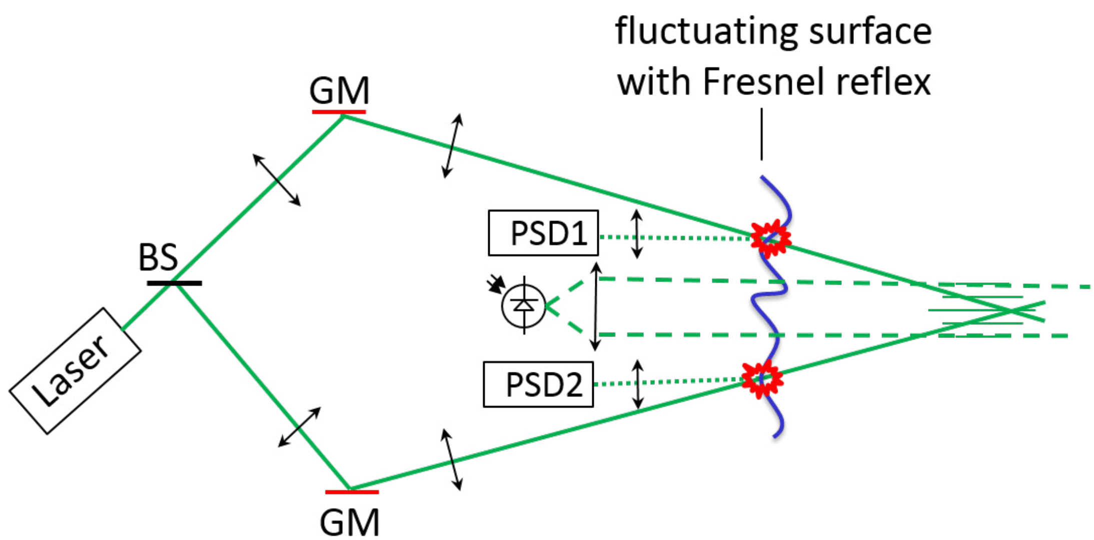

Fig. 1. Mach-Zehnder interferometer for velocity measurements with implemented dual adaptive optic system based on two-axis Galvanometer Mirrors (GM) and Position Sensitive Detectors (PSD) for evaluating the Fresnel reflex. The adaptive optics system compensates the tip and tilt error caused by the fluctuating gas-liquid interface.

A difficulty arises when the reflected beam is to be used for beam stabilization since it shows a different behavior because Snell’s law of refraction. We solved this problem by implementing Snell´s law into the control loop. In Fig. 1 the sketch of a second experimental setup is shown, where a correction of the beam tip and tilt is achieved by using the Fresnel reflex and using position sensitive devices (PSD) as simple wavefront sensors.
Whereas in astronomy the Strehl ratio is used for imaging systems to characterize the quality of the aberration correction of the AO system, for the non-imaging case considered here the rate of valid signals is used instead. The validation rate is given by the number of valid measurement signals with respect to the number of all acquired signals and depends

mainly on the interference visibility. It should be understood that in relation to the Fig. 1 a modified setup was used. In order to reduce the expense of the investigations, only one of the two laser beams were modulated by a galvanometer mirror (GM). The direction of the laser beam reflected at the water surface was detected by a Hartmann-Shack CCD camera, which is in this case analog to the PSD technique.
In Figs. 2a and 2b the mean validation rate and the mean standard deviation of the flow velocity measurements are displayed, respectively. The dependency is the mean amplitude of the distortion, i.e. the mean amplitude of the capillary water waves. Data were obtained from a characterization experiment which used a velocity reference to generate defined signals. It is obvious that the wavefront correction by the adaptive optics system results in a significant increase of the validation rate and a reduction of the measurement uncertainty.

3. CONCLUSIONS

Refractive index variations, caused by fluctuating interfaces can deteriorate the properties of laser-optic distance and velocity measurements. A lower rate of valid signals and an increased uncertainty can be the consequences. To overcome these limitations, the principle of wavefront correction by means of adaptive optics, which is commonly known from astronomy and ophthalmology, can be applied to laser measurement techniques as well. In this contribution, a Mach-Zehnder interferometer for fluid flow velocity measurements was presented, that was equipped with a dual adaptive optics system to corrected wavefront distortions caused by a fluctuating air-water interface.
Using the wavefront correction, the number of valid signals is improved significantly whereas the measurement uncertainty is reduced concurrently. Measurements in the presence of optical distortions can be performed in a shorter time and with a higher statistical reliability. We have introduced the Fresnel reflex as a new realization of a laser guide star. It enables measurements with backward scattering through media with discrete changes of the refractive index, i.e. optical interfaces, with only one optical access. Such measurements through disturbing fluid interfaces with only a single-sided optical access play an important role at several fields of fluid mechanics.
At convection research an improved understanding of heat transfer by turbulence can be achieved by measurements at liquid jets in gaseous atmosphere. Another example is the investigation of the energy efficiency of film cooling devices, where liquid film with film thicknesses below 1 mm on a structured, opaque substrate are employed. As a result, adaptive optics offers new perspectives for metrology at applications that were hardly accessible by measurement techniques so far.

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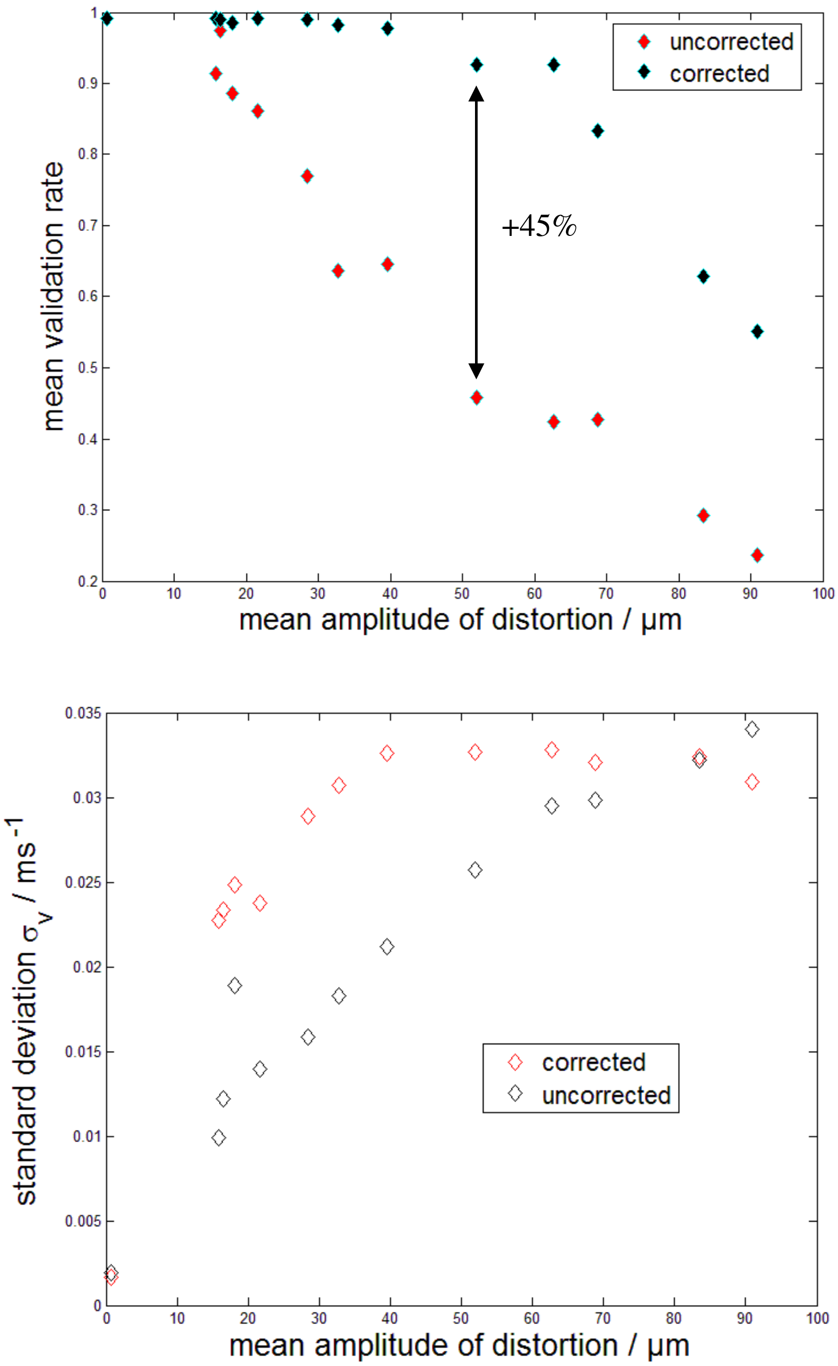

Fig. 2: Mean validation rate (top, green data: corrected, red data: uncorrected) and mean standard deviation (bottom, red data: corrected, black data: uncorrected) in dependence of the mean amplitude of the distortion (height of the water surface wave).

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